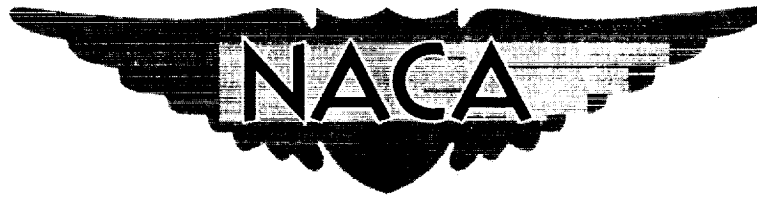


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RESEARCH MEMORANDUM

EVALUATION OF LIQUEFIED HYDROCARBON

GASES AS TURBOJET FUELS

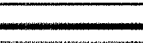
By Robert R. Hibbard

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NATIONAL ADVISORY COMMITTEE  
FOR AERONAUTICS

WASHINGTON

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## NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

## EVALUATION OF LIQUEFIED HYDROCARBON GASES AS TURBOJET FUELS

By Robert R. Hibbard

## SUMMARY

Liquid methane, ethene, and propane along with normally liquid hydrocarbon fuels are considered in this analytical report. It is shown that the lower molecular weight hydrocarbons are much superior to current JP-type fuels as heat sinks and that these more volatile fuels may be required with cooled-turbine engines. It is also shown that aircraft range will not necessarily suffer from use of low-molecular-weight fuels even though their density is low. The normally gaseous fuels would have to be handled at low temperatures, and the tank insulation requirements and handling factors are discussed herein. The relatively short times that aircraft can be held between fueling and takeoff is a severe disadvantage with some fuels. The availability and cost aspects are shown to be quite good with the lower molecular weight hydrocarbons.

## INTRODUCTION

Aircraft have always been forced to dissipate a considerable amount of heat in one way or another. For piston-engine airplanes, the largest heat load is, by far, for engine cooling; this load is of the order of 25 percent of the heat of combustion or about 5000 Btu per pound of fuel burned. The heat load for turbojet engines is a much smaller fraction of the heat of combustion. In either case this heat is easily rejected to the air at low subsonic flight speeds. However, with increasing flight speeds convective heat rejection to air first becomes less attractive and finally becomes infeasible at multi-Mach speeds because of the increasing aerodynamic drag of the convectors and the increasing stagnation temperature at the convector surfaces. Therefore, at high flight speeds, heat must be dissipated internally, that is, to some part of the aircraft or its load.

The fuel appears to be the most promising heat sink in future aircraft since it will be a large fraction of the gross weight, has a relatively high specific heat, and can be conveniently utilized. Fuel is now being used to accept the heat rejected from the engine lubricant.

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A much wider use of the fuel as a heat sink is probable in future aircraft, especially if cooled-turbine engines that reject heat to the fuel are developed.

The principle differences in heat-sink capacity between fuels lies in the temperature range over which they can be used. The limit for the lower temperature is set by the freezing point of the fuel, and the upper temperature limit is set by the temperature at which fuels degrade to the extent that exchanger or engine performance suffers. This upper limit has already been reached in some flight missions with some current jet fuels where solid degradation products have fouled lubricant-to-fuel heat exchangers and have clogged engine fuel injectors.

The need for fuels with greater heat-sink potentials suggests the use of low-molecular-weight hydrocarbons. Such fuels could be utilized between lower initial temperatures and higher final temperatures than can current jet fuels.

The low-molecular-weight hydrocarbons have much lower densities than conventional jet fuels, but slightly higher heats of combustion. For a given aircraft designed for JP-type fuels, the penalties induced by the lower density would certainly outweigh the gains due to the higher heat of combustion; aircraft performance would therefore be poorer with methane than with JP fuels. However, for an aircraft designed for a specific fuel, the effect of lower density and higher heat of combustion is not obvious; a detailed analysis is required.

The low boiling points and high vapor pressures of fuels such as methane and propane would certainly present new and possibly difficult operating problems both on the ground and in the air. While there is considerable experience with non-aircraft use of propane (liquefied petroleum gas) and less experience with liquid methane (natural gas), their use in aircraft would not be easy. The fuels would have to be refrigerated, and tank insulation would be required, which would raise new problems in refueling, pumping, and engine control.

Although only liquefied gaseous hydrocarbons have been mentioned, there may also be interest in fuels with molecular weights intermediate between these and the current jet fuels. Pentanes and aviation gasoline are examples. They could be handled as liquids without refrigeration, and their heat-sink capacities, while inferior to those of the liquefied gases, would be greater than those for jet fuels and might be sufficient for most applications.

Therefore, an analysis has been made of the potential value of the lower molecular weight hydrocarbons as fuels for turbojet-powered aircraft. The following fuels have been considered: methane, propane, ethene, an isopentane-isohexane blend, and aviation gasoline. Also included are a conventional JP-4 fuel, which is used for reference purposes, and a kerosene-type fuel having high thermal stability. Reported herein are the results of this analysis in terms of (1) capacities of the fuels to act as heat sinks, (2) ranges for two types of aircraft, each at a single flight condition, (3) estimates of combustion efficiency, (4) probable fuel handling problems, and (5) fuel availability and cost.

This report emphasizes the heat-sink capacities of fuels, and supporting data and figures are presented. The fuels are compared as to range in design-point aircraft through calculations made by H. M. Henneberry of the NACA Lewis laboratory. Estimates of the heat-rejection loads from cooled-turbine engines were made by R. R. Ziemer also of the NACA Lewis laboratory. The procedures used by Messrs. Henneberry and Ziemer are quite complex and are not included in this report; only their final results are shown.

## FUELS

Seven fuels are treated in this analysis. Three are single-component fuels (methane, ethene, and propane), and one is a low-freezing-point blend of 42 percent isopentane and 58 percent isohexane (2-methyl pentane). The remaining three are commercial wide-boiling-range fuels. The aviation gasoline and the JP-4 fuel are those of reference 1; the JP-4 fuel is the average quality fuel of this grade (ref. 1). The JP-z fuel is a stable, highly naphthenic kerosene-type fuel. Inspection data for this material were obtained at the NACA Lewis laboratory. A general description of these fuels is given in the appendix.

A few physical and combustion properties for the seven fuels are listed in table I. Additional properties over a range of temperatures are plotted in figures 1 to 3. Figure 1 gives enthalpy-temperature curves drawn with the zero enthalpy base of each fuel at its freezing point. Figure 2 shows vapor-pressure - temperature curves and figure 3, the density-temperature relations. The data listed in table I and shown in figures 1 to 3 were either taken directly or calculated from data and methods given in references 1 to 5. Details are outlined in the appendix.

## HEAT-SINK CAPACITIES AND REQUIREMENTS

There are many possible heat sources in present and proposed turbojet-powered aircraft which do or could use the fuel as a heat sink. Of these sources the following three are responsible for the thermal-instability problems which are now being encountered with some fuels:

(1) The fuel pump. This is a source of heat at low flow rates, since fixed-capacity pumps are used in many engines. When the engine demands less than full pump capacity, as, for example, at high-altitude cruise, the fuel is recycled through the pump. This results in the conversion of mechanical work into heat.

(2) The engine lubrication system. In current turbojets the oil both lubricates and cools the engine. The resulting heat is dissipated to the fuel in the oil-to-fuel exchangers of these engines. In current engines, the temperature of the incoming oil may reach approximately 350° F and the temperature of the outgoing fuel nearly as high. These temperatures probably will go higher as more-stable lubricants are developed.

(3) Heat transfer from the combustion process which further heats the fuel between exchanger and atomizer.

While these are the only sources rejecting heat to the fuel in current aircraft, there are other sources that might so use the fuel in future aircraft. These include:

- (1) Refrigeration cycles for cabin cooling
- (2) Direct exchange or refrigeration cycles for cooling electronics
- (3) Similar cooling of aircraft hydraulic systems
- (4) Cooling of hot engine parts

As is shown later, this last source becomes a major heat load in aircraft with cooled-turbine engines.

While the heat loads being rejected to the fuel can be estimated for current and proposed turbojet engines, there is little basis for making similar estimates of future airframe requirements because the designers of airframes have little idea of the fuel heat-sink capacity that will be available for their use. In this section we first, estimate the heat-sink capacities of the several fuels, second, indicate the expected heat loads to be put thereon by the engines, and finally, estimate the heat-sink capacity remaining in the fuel for other uses.

## Heat-Sink Capacities of Fuels

The amount of heat that can be rejected to a unit weight of fuel is given by

$$Q = \int_{T_1}^{T_2} c_p dt + H_{vap} \quad (1)$$

where

$Q$  amount of heat

$T_1, T_2$  initial and final temperatures

$c_p$  specific heat

$H_{vap}$  latent heat of vaporization, available only if the fuel changes phase when acting as a heat sink

The amount of heat  $Q$  can be easily taken from the enthalpy-temperature curves of figure 1 provided that initial and final conditions are known.

For this analysis two initial temperatures were used for each fuel. The first was the normal boiling points for methane, ethene, and propane, and 100° F for the remaining, normally liquid fuels. The second initial temperature was 10° F above the freezing point of each fuel except for aviation gasoline for which the 15-centistoke temperature (-160° F) was used. This latter condition was selected for cases where maximum heat-sink capacity is desired.

The selection of the final temperatures  $T_2$  was more difficult. The upper limit for  $T_2$  is imposed by the degradation of the fuel, and there are three degradation reactions involved. These are illustrated for JP-4 fuels in figure 4 where reaction rate is shown as a function of temperature. For ideal systems, a plot of log rate against the reciprocal of absolute temperature gives a straight line, and such systems were assumed in figure 4.

The lowest temperature reaction shown in figure 4 is for the formation of insoluble gum. This is shown as a band covering two JP-4 fuels of differing gum-forming qualities. The two experimental points were calculated from data given in reference 6, and the slope of the shaded area is calculated assuming an activation energy of 20 kilocalories (ref. 1). At 400° F, for example, the rate constant for insoluble gum is between  $2 \times 10^{-7}$  and  $2 \times 10^{-6}$  second. This also equals the fractions of gum formed per second, that is,  $2 \times 10^{-7}$  to  $2 \times 10^{-6}$  fraction per second. These gum-forming

rates represent limits from only one study (ref. 6); batches of jet fuels probably are being produced which are both poorer and better than these. Therefore, the range possible for insoluble gum formation is wider than that shown in figure 4.

The next reaction shown in figure 4 is for thermal cracking. Although there is considerable literature on the cracking of various petroleum fractions, no data are known for JP-type fuels. The line shown here was estimated from reference 7 and is drawn halfway between lines for gas oil and for naphtha. Since JP-4 fuel is intermediate in volatility between these stocks, this line should represent a reasonable approximation for the jet fuel. At 400° F the cracking rate is very slow and well below  $10^{-9}$  fraction cracked per second. Considerably higher temperatures, of the order of 600° to 800° F, are required before the cracking rate becomes equal to the gum-forming rate at 400° F.

The final reaction shown in figure 4 is the shaded area to the left labeled coke formation. This is for coke formed as a side reaction in the cracking reaction. Unlike the cracking reaction where rates can be fairly well set as a function of temperature alone, the coking reaction is a complex function of temperature, pressure, reactant phase, and reactor surfaces. No data are available which will accurately define the coking rate, and the shaded portion is shown in figure 4 for illustrative purposes only. The coking rate is necessarily much lower than the cracking rate and is so shown.

Of the three degradative processes shown in figure 4, only the rates for the cracking reaction are known or can reasonably be estimated for all the fuels used in this analysis. Therefore, the upper temperature limit for use as  $T_2$  in equation (1) is largely based on this reaction alone.

Cracking rates for the several fuels are shown as functions of temperature (solid lines) in figure 5. These rates are based on reference 7 and the following arguments:

- (1) Methane and propane rates were taken directly from reference 7.
- (2) Ethene is slightly more resistant to cracking than ethane, and therefore the line for ethene was drawn for a slightly lower rate than that shown for ethane in reference 7.
- (3) The isopentane-isohexane rate is the same as that given for the pentanes in reference 7.
- (4) Aviation gasoline was estimated to have the same rate as naphtha of reference 7.



(5) As previously stated, the JP-4 fuel was assumed to be intermediate between gas oil and naphtha in cracking rate.

(6) The JP-z fuel is a highly naphthenic (cycloparaffinic) fuel. Reference 7 shows cyclohexane to crack at one-tenth the rate of n-hexane. Therefore, the rate of JP-z fuel was taken as one-tenth that for JP-4 fuel which gives it the same rate as that for the isopentane-isohehexane blend.

Also shown on figure 5 are dotted lines for 1.0 and 0.01 percent of the fuel cracked in 10 seconds.

Cracking, per se, should present no fuel-system problems. However, the cracking reaction is accompanied by side reactions leading to the formation of solid deposits. It was assumed that (1)  $10^{-6}$  fraction of solids would be the maximum amount that the engine could tolerate, (2) the rate of formation of solids would be  $1/1000$  the cracking rate, and (3) fuel residence time at the high temperature would be 10 seconds. Based on these three somewhat arbitrary assumptions, the maximum tolerable amount of cracking reaction would be  $10^{-3}$  fraction per second or 0.01 percent in 10 seconds. This rate is shown by the lower dotted line in figure 5, and the maximum allowable temperature  $T_2$  can be taken from the intercept of this dotted line with the reaction rate line for each fuel.

The final consideration in the use of equation (1) is whether the fuels will be vaporized or not when acting as heat sinks. The normally gaseous fuels, methane, ethene, and propane, will certainly permit vaporization. It was also assumed that the isopentane-isohehexane blend and aviation gasoline could also be vaporized without excessive exchanger fouling. JP-4 fuels of current quality would almost certainly foul exchangers badly if complete vaporization were attempted, and therefore this fuel was maintained in the liquid phase for this analysis. However, it is possible that the highly stable, narrow-boiling-range JP-z fuel could be vaporized cleanly. For this last fuel the analysis was made both with and without vaporization.

From the above considerations, the heat-sink capacities of the several fuels were estimated using figures 5 and 1. Results in both Btu per pound and fractions of heats of combustion are listed in table II. JP-4 fuel was assumed to be gum limited and not cracking limited (fig. 4), and a final temperature of  $400^{\circ}$  F was used. It was found that methane could be heated to  $1245^{\circ}$  F before exceeding 0.01 percent cracking. This temperature is believed to be too high for effective use as a heat sink. Therefore, a final temperature of  $1000^{\circ}$  F was arbitrarily set for this fuel, and data to this temperature are also listed in table II.

The available heat-sink capacities range from a low of 165 Btu per pound for JP-4 fuel initially at  $100^{\circ}$  F to a high of approximately 1300 Btu per pound for methane. The data in table II clearly show the superior heat-sink qualities of the lower molecular weight hydrocarbons.

### Heat-Sink Requirements of Engines

Three turbojet engines are used in this section and in the subsequent performance analysis. These engines are

Engine A: A turbojet with a 2000° R (1540° F) turbine-inlet temperature and with afterburning.

Engine B: An afterburning engine with a 2500° R (2040° F) turbine-inlet temperature. Both turbine and stators are lightly cooled.

Engine C: A heavily cooled nonafterburning engine with a 3000° R (2540° F) turbine-inlet temperature.

Engine A represents an uncooled engine of recent design. Engines B and C were selected on the basis of the expected trends in engine development required for high-altitude, supersonic flight. The higher turbine-inlet temperatures of these last two engines would give higher specific thrust (thrust per pound of air) and improved performance in both fighters (ref. 8) and bombers (ref. 9). The use of higher inlet temperatures with turbine cooling would also result in large decreases in engine specific weight (pounds of engine weight per pound of thrust) as shown in reference 10.

Some of the many possible schemes of cooling turbine stator and rotor blades are discussed in reference 10. As the flight Mach number, and thus the ram-air temperature, is increased, some of these methods have insufficient heat capacity or require large heat exchangers to take care of the turbine cooling load. Thus the excess heat must be dissipated to either the aircraft or the fuel. In order to obtain a relative comparison of the heat capacities of the various fuels, it is assumed that the entire turbine cooling load must be absorbed by the fuel.

Published data are available on the heat loads of uncooled engines of the type of engine A. Reference 11 gives Btu per hour loadings and resultant fuel temperatures for several flight conditions. Reference 12 gives data which generally confirm reference 11. The two flight conditions selected from reference 11 for use herein are Mach 1.0 and Mach 1.9, both at a 60,000-foot altitude. Data were calculated to the following heat loads in terms of fractions of the heats of combustion:

Flight condition		Heat load, fraction of heat of combustion		
Mach number	Altitude, ft	From pump	From oil	Total
1.0	60,000	0.002	0.005	0.007
1.9	60,000	.0005	.002	.0025

The more severe condition is at the lower flight speed; this is because (1) the pump conversion of work to heat is greater at the lower speed, lower flow rate conditions, and (2) the time rate of heat rejection to the lubricant and thence to the fuel is substantially constant and thus results in higher fuel temperatures at the lower flow rates.

There is no analysis of the pump and lubricant heat loads for engines B and C but an analysis of the turbine cooling loads has been made at the NACA Lewis laboratory. These loads are based on heats of combustion and are as follows for three flight conditions:

Flight condition		Turbine cooling load, fraction of heat of combustion	
Mach number	Altitude, ft	Engine B	Engine C
1.0	40,000	0.006	0.024
1.9	60,000	.006	.027
2.5	65,000	.006	.028

The second flight condition is the same as that used for the pump and lubricant loads of engine A. These heat loads were calculated for engines in the earliest stages of design. While they are reasonable values, these engines as finally developed could impose considerably greater or smaller loads on the fuel depending on a variety of factors.

To the above turbine cooling loads for engines B and C can be added estimates of the amounts of heat arising from the fuel pump and the lubrication cycle. This was done by assuming:

(1) The heat from the pump would be 0.001 of the fraction of the heat of combustion at the lowest flight speed, and at the higher speeds this heat would be negligible.

(2) The lubricant cycle heat rejection at Mach 1.0 and 40,000 feet for engines B and C would be the same as for engine A at Mach 1.0 and 60,000 feet, that is, 0.005 of the fraction of the heat of combustion. This load would be 0.002 of the fraction at the higher flight speeds. With these assumptions, total heat loads as fractions of the heats of combustion are summarized in table III for the three engines. Inspection of this table clearly shows the increased heat-sink capacity that will be required for cooled-turbine engines if the cooling is done through cycles that reject the heat to the fuel. For the conditions listed and with conventional fuels, the uncooled engine A would reject 45 and 130 Btu to each pound of fuel; for the lightly cooled engine B the values are 150 and 220 Btu per pound of fuel. The heavily cooled engine C would reject about 550 Btu to each pound of fuel.

### Heat-Sink Capacity Remaining for Non-Engine Use

Table II summarizes the heat-sink capacity for the several fuels, and table III shows the estimated demand for three types of engines. From these data the heat-sink capacity remaining for other uses can easily be estimated. These estimates are listed in table IV. For each fuel and initial fuel temperature, the available heat sink from table II is shown along with the engine requirements from table III. The differences are shown as both fractions of the heats of combustion and as Btu per pound; this difference is available for such non-engine uses as cabin, electronic, and hydraulic-system cooling.

Table IV(a) shows the amount of heat sink remaining from engine A. At the lower flight speed conditions, this ranges from 35 Btu per pound for uncooled JP-4 fuel to 970 Btu per pound for cooled methane. At the higher flight speed there is slightly more capacity available for non-engine use. The low value of 35 Btu per pound for JP-4 fuel shows this fuel to be marginal in its ability to cool the engine alone. If the sample had been less stable, for example, one that formed excessive gum at 325° F, then operational problems would be expected even though no heat loads other than those from the engine were imposed on the fuel. In any case, there is little heat-sink capacity left for other airframe demands. With all the other fuels, and especially with the normally gaseous hydrocarbons, there is a surplus heat-sink capacity.

Similar data for engine B are shown in table IV(b). For this lightly cooled engine the JP-4 fuel is inadequate unless precooled to -75° F. However, the heat-sink capacities of all the other fuels appear adequate for most needs.

Table IV(c) presents data for the heavily cooled engine C. In this case JP-4 fuel is completely inadequate even when precooled. The JP-z fuel and aviation gasoline would supply the engine demands if precooled; however, the JP-z fuel may be marginal in this respect. The low-molecular-weight hydrocarbons all have ample heat-sink capacity remaining over engine demands.

The data in table IV show the most important reason for considering the low-molecular-weight hydrocarbons as turbojet fuels. If turbojet development goes along the path of heavily cooled engines such as engine C, and if the fuel acts as the ultimate heat sink, then it appears necessary to use fuels having lower molecular weights than those of current aviation fuels.

### AIRCRAFT RANGE

There is no doubt that the low-molecular-weight hydrocarbons are far superior to the conventional jet fuels as heat sinks. There is, however, a

question as to what extent aircraft range would be penalized by the quite low densities of these fuels and to what extent range would be augmented by their slightly greater heats of combustion. As mentioned in the INTRODUCTION, volume-limited aircraft designed for JP-type fuels would have a much reduced range if fueled, for example, with liquid methane. However, for a series of aircraft, each designed for a specific fuel, the relative importance of low density and high heat of combustion can be determined only through a detailed analysis. This section presents the results from one such analysis made at the NACA Lewis laboratory.

There are a large number of missions which could be studied and a variety of aircraft and engine combinations which could be used to accomplish each mission. Therefore, fuels could be rated on an almost infinite number of mission, aircraft, and engine combinations. The purpose herein is to examine two arbitrarily selected cases to see whether it would be practical, from a range standpoint, to use low-molecular-weight hydrocarbons as turbojet fuels.

Two quite different missions and aircraft types were selected. The first case was an interceptor action of a 25,000-pound-net fighter. The second was a bombing mission of a 150,000-pound-net bomber. Both missions were flown all the way at Mach 2.5 with the bomber at 65,000 feet over the target and with 5 minutes of combat action at 65,000 feet for the fighter. The assumptions as to fuel-tank geometry, ullage, and insulation are given in a subsequent section. Both aircraft were powered with the three turbojet engines previously described: engine A, afterburning with a turbine-inlet temperature of  $2000^{\circ}\text{R}$ ; engine B, afterburning with a turbine-inlet temperature of  $2500^{\circ}\text{R}$ ; and engine C, nonafterburning with a turbine-inlet temperature of  $3000^{\circ}\text{R}$ . Combustion efficiencies of 98 percent for the main engine and 90 percent for the afterburner were assumed in all cases.

The comparison of range as influenced by fuel variables is given in table V for both missions with engines B and C. These data are given in terms of range relative to that obtainable with JP-4 fuel even though engine C is not operable with this fuel. A similar analysis was not made for engine A, since the principal interest in low-molecular-weight hydrocarbons is for cooled-turbine engines. For these aircraft, each designed for a specific fuel, there is no penalty induced by the low densities of the lower molecular weight hydrocarbons. In fact, the range with these fuels is greater than with the JP-type fuels, because the benefits derived from the higher heats of combustion more than overbalance the penalties due to low density.

It must be emphasized that the comparison shown in table V is based on an arbitrary selection of missions, aircraft, and engines. Other, equally plausible, sets of assumptions could have been selected which

would have influenced the ratings of these seven fuels. It is not the purpose of this report to claim any specific benefits in range for the low-molecular-weight hydrocarbons but only to point out that the low densities of fuels such as liquid methane will not necessarily cause a loss in range.

### COMBUSTION PERFORMANCE

In the preceding range analysis, equal combustion efficiency was assumed for all fuels. Of the seven fuels only JP-4 fuel and aviation gasoline have been tested in fuel-scale engines. Nevertheless, it is believed that reasonable estimates of combustion behavior can be made for all the fuels on the basis of single-combustor and bench-scale data for these and similar fuels.

Combustion efficiency is a function of engine design, engine operating conditions, and fuel variables. Operating conditions and their effect on efficiency can be described in terms of a correlating parameter developed in reference 13. The reciprocal of this parameter is  $V/PT$ , where  $V$  is the reference air velocity through the combustor and  $P$  and  $T$  are inlet-air pressure and absolute temperature, respectively. Operating conditions become more severe as  $V/PT$  increases, that is, combustion efficiency decreases with increasing air velocity and with decreasing pressure and temperature.

Numerical values for the  $V/PT$  parameter were calculated for a few flight and engine speed conditions for the engines used herein. These values are dependent on engine compression ratio, compressor capacity, and combustor cross-sectional area but are not dependent on turbine cooling factors; therefore, values of the parameter are the same for all engines. The results are as follows:

Altitude, ft	Mach number	Engine speed, percent rated	$V/PT$ , ft/(sec) (lb)(°R)
65,000	2.5	100	$10 \times 10^{-6}$
80,000	2.5	100	20
65,000	1.0	100	110
65,000	1.0	80	240
65,000	1.0	Wind- milling	1800

Conditions become more severe as altitude increases, as Mach number decreases, and as engine speed decreases.

With turbojet combustors of advanced design, combustion efficiencies above 90 percent can be obtained at parameter values below approximately  $150 \times 10^{-6}$ , and, at values below approximately  $50 \times 10^{-6}$ , the efficiencies are substantially 100 percent (e.g., ref. 14). The preceding table shows that the Mach 2.5, 65,000-foot-altitude condition used in the range analysis is very mild for combustion ( $V/PT = 10 \times 10^{-6}$ ) and therefore combustion efficiency should be close to 100 percent. For this reason, a combustion efficiency of 98 percent was assumed for all fuels in the range analysis. Afterburner conditions are much more severe, and an afterburner efficiency of 90 percent was assumed.

Although it appears the combustion efficiencies will be near 100 percent for all the fuels at Mach 2.5 conditions, there are other flight conditions (cruise and loiter) where efficiencies may be much lower. It is desirable to compare the combustion performance of the seven fuels under more severe conditions. The single-combustor data of references 14 and 15, while incomplete, give some information in this regard.

In reference 14 an advanced design combustor was run on gaseous propane, liquid JP-4 fuel, and partially vaporized JP-4 fuel. Their performance at a combustor temperature rise of  $680^\circ \text{F}$  is shown as a function of the  $V/PT$  parameter in figure 6. Propane gives slightly higher efficiencies than JP-4 fuel at all conditions, and at severe conditions the liquid JP-4 fuel is considerably the poorest. This figure shows the benefits derived from using vaporized fuel at the present state of the art of combustor design. Therefore, improved combustion performance may be expected at severe conditions when fuels are vaporized in acting as heat sinks.

Another comparison between two of these fuels can be made from data presented in reference 15. Propane and ethene were among the fuels that were tested, and data are shown in the following table for two severe conditions of  $V/PT$ :

Fuel	Combustion efficiency, percent	
	$V/PT = 125 \times 10^{-6}$	$V/PT = 223 \times 10^{-6}$
Propane	80	62
Ethene	97	79

The combustor used in this work (ref. 15) was smaller and not as highly developed as that used in the work of reference 14; therefore, the efficiencies listed in the table for propane are lower than those shown in figure 6. However, ethene gave considerably higher efficiencies than did propane.

The performances of methane and propane in an experimental annular combustor have been compared (NACA unpublished data). Both fuels gave substantially the same combustion efficiencies up to a combustion severity parameter value of  $200 \times 10^{-6}$ ; at more severe conditions methane gave lower efficiencies than propane. It was also found that the combustion stability limits in terms of fuel-air ratio were narrower for methane than for propane; this could be anticipated from the somewhat narrower range of flammability limits shown for methane in table I.

High fundamental flame velocity is a desirable property for turbojet fuels (refs. 15 and 16). Wide flammability limits should extend combustor stability ranges. However, inspection of table I shows that all the fuels except ethene have similar fundamental flame velocities, and for most of the fuels the flammability ranges in terms of fuel-air ratio do not differ greatly. From these fundamental considerations and from the single-combustor data previously cited, it appears that ethene should give the highest efficiencies at severe combustion conditions and that JP-4 fuel, because it alone is injected as a liquid, should give the lowest. The other fuels should be nearly the same, although methane may be slightly the poorest of the remaining five fuels. This conclusion is necessarily qualitative, since a quantitative comparison could be made only if a series of combustion chambers were designed and developed, each to give optimum performance with a specific fuel.

Besides combustion efficiency, fuels must also be considered as to their probable coke- and smoke-forming tendencies. These undesirable properties increase with increasing aromatic content and with decreasing volatility (ref. 17). All the fuels except the JP-z fuel should be clearly superior to JP-4 fuel as to their coking and smoking tendencies, since they are all more volatile and have lower aromatic contents. The JP-z fuel is lower in aromatics than the JP-4 fuel but is less volatile. These two effects might nearly cancel each other out making JP-z and JP-4 fuels much the same in regard to coke and smoke formation. In general, low-molecular-weight fuels should present no new problems in this regard, and all but the JP-z fuel should greatly ease combustor coking and smoking problems.

#### FUEL SYSTEMS

Low-molecular-weight hydrocarbons have been shown to be clearly superior to the conventional JP-type fuels in heat-sink capacity and equivalent or slightly better in both range and combustion characteristics. The greatest objection to their use would lie in their very high volatility, which would require that they be handled at either high pressures, low temperatures, or both. The degree of difficulty in using the fuels considered herein would vary greatly. Methane, with its low critical temperature, would have to be kept very cold, while aviation gasoline



would require only some tank pressurization at high altitudes. This section discusses some aspects of the fuel handling problems associated with low-molecular-weight hydrocarbons.

### Aircraft Fuel Tank

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Three factors must be considered in the design of the insulated fuel tanks required for low-molecular-weight hydrocarbons. First, the in-flight rate of fuel vaporization must not exceed the rate that fuel is consumed and preferably should be a small fraction thereof. Second, it would be desirable to have sufficient insulation so that the aircraft could be held on the runway a reasonable length of time without excessive fuel loss. And third, the weight and volume of insulation are detrimental to aircraft performance and should be kept to a minimum. For this analysis it was assumed that the fuel tanks were cylindrical bodies with hemispherical ends and that expanded polystyrene was used as insulation. This material has a density of 1.3 pounds per cubic foot and a thermal conductivity of 0.010 and 0.020 Btu per hour per square foot at  $-250^{\circ}$  and  $0^{\circ}$  F, respectively (ref. 18). The interceptor tanks were assumed to be 5.0 feet in diameter and the bomber tanks 8.0 feet. Tank lengths varied with the density of the fuels and ranged from 10 to  $20\frac{1}{2}$  feet for the interceptors and from 26 to 52 feet for the bombers.

Preliminary calculations showed that less than  $1/4$  inch of expanded polystyrene was sufficient to keep fuel vaporization rates far below the engine consumption rates for all fuels. The gain in range obtained in reducing insulation thickness to less than  $1/4$  inch is well below 1 percent for these aircraft; therefore,  $1/4$ -inch insulation was used for all the fuel tanks considered herein.

Heat-transfer calculations were made for the Mach 2.5, 65,000-foot-altitude condition using methods similar to those used in reference 19. For the most severe condition for methane at an initial temperature of  $-259^{\circ}$  F in the fighter, it was found that only 1.2 percent of the fuel load needed to be vented to maintain a tank pressure of 1.0 atmosphere absolute. Even this small amount of fuel need not be vented, if it is assumed that the fuel tanks of these aircraft could be pressurized to 2 atmospheres. This would permit the use of the sensible heat capacity of the fuel as it goes from the boiling temperature at 1 atmosphere to the boiling temperature at 2 atmospheres. Under these conditions the sensible heat capacity of the fuel is several times the total heat leak through the insulation during flight.

A small amount of insulation,  $1/4$  inch of expanded polystyrene, for example, is ample to keep fuel losses in flight to negligible amounts for all the fuels considered herein.

The second factor to be considered is the time that an aircraft can be held on the runway after fueling when 1/4 inch of expanded polystyrene is used as insulation. In this case only the sensible heat for a change from 1 to 2 atmospheres could be used provided that the tanks could stand this pressure and that no venting losses were permitted. This sensible heat capacity was divided by the hourly heat-transfer rates calculated for an 80° F ambient temperature to give holding times for zero loss of fuel. These holding times are listed in table VI for the normally gaseous fuels. The normally liquid fuels could be held indefinitely. For the interceptor these times range from 3.8 hours for methane initially at its normal boiling point to 94 hours for an aircraft fueled with propane cooled to just above its freezing point. The holding times for the bomber range from 6.6 to 167 hours with the same fuel situations.

The moderate holding times shown in table VI appear to be one of the greatest obstacles in the use of low-molecular-weight hydrocarbons as aircraft fuels. Aircraft could not be kept in constant readiness without auxiliary refrigeration equipment. The disadvantage is much greater for interceptor operation both because the holding times are shorter and because the preparation time prior to takeoff is apt to be much less. Cooling the fuel below its normal boiling point is some help.

Another form of operation might be to permit the fuel to be vaporized at 1 atmosphere through tank vents and to top off the tank just prior to takeoff. The rate of vaporization for the normally gaseous fuels would be as follows:

Fuel	Vaporization rate, percent of fuel load per hour	
	Interceptor	Bomber
Methane	1.5	0.9
Ethene	1.0	.6
Propane	.7	.4

A final consideration in the use of liquefied hydrocarbon gases is that the tank outer surfaces would be below 32° F while the aircraft is on the ground. Therefore frost or ice would be collected. It is not known whether the additional weight so acquired would hamper aircraft operation.

#### Ground Handling Factors

The storage and handling of the normally liquid fuels considered herein would present no new problems, although use of the isopentane-isohexane blend might require some extra precautions because the blend

\$0.03 per million Btu, and the wholesale price at distant consuming points as high as \$0.21. The price shown in table VII is an average of well, industrial, commercial, and residential prices.

An estimate was made of the cost of liquefying natural gas based on the plant designed for the process given on page 1710 of reference 5. This plant can liquefy  $4 \times 10^6$  cubic feet of gas per day using 2700 horsepower. Cost estimation was based on: (1) 300 days of operation per year, (2) a plant cost of \$1,000,000 and an annual depreciation, maintenance, tax, and profit of 25 percent of this figure, (3) power at \$0.015 per kilowatt-hour, and (4) \$50,000 per year for labor and supervision. With these assumptions the cost of liquefying natural gas is \$0.43 per  $10^6$  Btu. This cost was added to the previously estimated cost of the gas and is shown in table VII. The cost of liquid natural gas is about two-thirds the current cost of JP-4 fuel on a Btu basis.

#### Ethene

Ethene is made by the drastic cracking of natural gas or petroleum fractions. A product with 95 to 99.9 percent purity is made which is used for a variety of petrochemicals. The present and projected production of this gas shown in table VII were taken from reference 21. The price listed is the median value between \$0.03 and \$0.065 per pound given in reference 21.

#### Propane

As liquefied petroleum gases this fuel is very widely used. Both the availability and the cost data shown in table VII are from reference 21. The cost shown is for a liquid at ambient temperatures. This liquid would have to be cooled to near its normal boiling point ( $-44^\circ$  F) before it would be usable as an aircraft fuel. The cost of the fuel so cooled would be slightly higher than the value shown.

#### Isopentane-Isohexane Blend

In 1945 isopentane and isohexane were produced at the rate of 55,000 and 10,000 barrels per day, respectively. Assuming the isohexane to be the limiting component, the blend could have been produced at the rate of 17,240 barrels per day or  $2.6 \times 10^8$  gallons per year. The 1960 potential is based on simply doubling the 1945 supply. Probably much more could be made if refinery processing were revised to make this blend. The cost estimate is based on large-quantity purchases made by the NACA in past years.

is quite volatile (vapor pressure of 0.9 atm at 100° F). However, new types of storage and fuel handling techniques would be required for the normally gaseous fuels.

Propane is stored and transferred under pressure in everyday practice as liquefied petroleum gases. The pressures are moderately high ( $12\frac{1}{2}$  atm at 100° F, 23 atm at 150° F) but are easily managed on the ground. However, fueling an aircraft would require the propane to be cooled to near its normal boiling point of -44° F. This could be done by auxiliary refrigeration or by self-refrigeration. In the latter case the liquid at storage temperature and corresponding pressure would be discharged to tanks at 1 atmosphere; about half the fuel would be lost to vapor and half converted to liquid at -44° F if the storage temperature were 100° F.

Both methane and ethene would have to be stored either as gases or as refrigerated liquids. Methane would present the greater problems. A design and economic study on the liquefaction and storage of natural gas as a liquid is given in reference 20. The economic factors are as of 1941 and are now outdated. Recent reliable estimates have indicated that a well insulated tank holding 750,000 gallons of the liquefied gas would now cost about \$350,000 or about \$0.50 per gallon; this latter figure compares not too unfavorably with estimated costs of from \$0.10 to \$0.25 per gallon for the storage of conventional liquid fuels. Therefore, it may be assumed that the bulk storage of liquid methane is both possible and not too expensive. Ethene would present similar, but lesser, problems than those that would be encountered with methane. Both boiling point and critical temperatures for ethene are considerably higher than those for methane.

#### AVAILABILITY AND COST

Availability and cost are always important factors in considering the potential of new types of fuels. Rough estimates as to availability and cost have been made and are summarized in table VII. The bases on which they were made are discussed in the following section.

#### Methane (Natural Gas)

Natural gas generally contains over 90 percent methane with the remainder being mostly higher molecular weight hydrocarbons. Production rates, both actual and potential, based on reference 21 are listed in table VII. In 1950 the price of natural gas at the well was as low as

### Aviation Gasoline

The current availability of aviation gasoline shown in table VII is a recent production rate for all grades (ref. 22). The fuel considered in this report is aviation gasoline only in terms of volatility and with no octane requirement. The availability of this material would be much greater, and the 1960 estimate is based on 20 percent of the barrel being converted into this type of fuel with crude runs of 10,000,000 barrels per day. The cost shown is not that for current aviation gasolines but rather a somewhat lower figure which appears reasonable for a fuel without octane number requirements.

### JP-4 Fuel

The current availability of JP-4 fuel is the present production rate for all types of jet fuel (ref. 22). The estimated potential is based on the assumptions used for a modified aviation gasoline. The cost is the approximate current price of jet fuel.

### JP-z Fuel

The JP-z fuel used as an example herein is a special item made by extensive refining of a particular type of crude petroleum. As such its present availability is very low and its cost high. The estimated availability for 1960 is for a highly refined kerosene-type fuel assuming that it could be made to the extent of 5 percent from all crude sources.

### Comparison Among Fuels

A comparison of availability and cost can best be made on a Btu basis. Inspection of table VII shows the estimated 1960 availability of methane, modified aviation gasoline, JP-4 fuel, and stable kerosene (JP-z fuel) all to be greater than the current production rate of aviation gasoline and jet fuel combined. The 1960 propane potential is just about the same as this current production rate. The probable availability of ethene and the isopentane-isohexane blend are much lower. However, the very high availability of methane is for a gaseous fuel; the amount of liquefied natural gas which could be used would be very much less unless a major effort were made towards building liquefaction units. Also a factor is the fact that the essential non-aircraft requirements have not been considered in any of this presentation.

As to cost, both methane and propane appear quite attractive and are cheaper than current jet fuels. Only the cost of JP-z fuel is unusually high; this cost probably is due to the very small production of this material at the present time.

## SUMMARY OF RESULTS

While it is qualitatively obvious that the low-molecular-weight hydrocarbons are superior to JP-type fuels as heat sinks, this analysis has attempted to compare, quantitatively, several fuels for this purpose. It sought to determine whether it may be necessary to go to such extremes as using, for example, liquid methane as a fuel for high-performance aircraft. For the aircraft, engines, and missions and based on the assumptions used herein, it is shown that cooled-turbine engines will require a greater heat-sink capacity than current jet fuels can provide. Liquefied methane, ethene, and propane can be used even with heavily cooled engines and still have sufficient heat-sink capacity to meet other aircraft needs. An isopentane-isohexane blend can also fulfill engine requirements, but little sink capacity is left for other uses. Modified aviation gasoline is borderline in meeting engine requirements alone, and the heavier current jet fuels are not capable of cooling engines with heavy turbine cooling loads.

In regard to aircraft performance with the several fuels and for the flight plans considered, it is shown that the range obtainable with the liquefied gases is slightly greater than that with conventional fuels provided that the aircraft used are each designed to a specific fuel. This increase in range is due to the fact that the increased heat of combustion of the low-molecular-weight fuels more than compensates for their low density. As to combustion efficiency, the low-molecular-weight hydrocarbons with vapor injection should all give somewhat better burning characteristics than current turbojet fuels with liquid injection; ethene should be outstanding in this respect. As to stability limits, methane may be slightly poorer than other vapor fuels.

The greatest complication in the use of liquefied gases lies in their high vapor pressure and the necessity of using refrigeration and adequate tank insulation. The insulation requirements in flight are not severe, and a 1/4-inch thickness should suffice. However, the times that a fueled aircraft could be held ready on the ground is relatively short; methane is especially poor in this regard and in an interceptor it could be held for less than 4 hours on an 80° F day with no auxiliary refrigeration.

The problem of external icing of fuel tanks may also be encountered with refrigerated fuels. The factors of fuel liquefaction and storage, ground handling and refueling, and aircraft pumps and controls would present many new but apparently not impossible operating problems.

The cost and availability picture appears quite good for several of these fuels. The availability potential for methane as natural gas is very high, although a major effort would be required for liquefaction equipment if this fuel were to find widespread aircraft uses. There also

appear to be sufficient quantities of all the fuels considered herein to meet any special mission needs.

Lewis Flight Propulsion Laboratory  
National Advisory Committee for Aeronautics  
Cleveland, Ohio, September 26, 1956

## APPENDIX - FUELS

The seven fuels considered in this report have the following general characteristics:

(1) Methane, the lowest molecular weight hydrocarbon, has one of the lowest freezing points ( $-296^{\circ}$  F) and is the most thermally stable of the hydrocarbons. It has the highest gas-phase specific heat and the highest latent heat of vaporization and is the hydrocarbon fuel with the greatest heat-sink capacity. It has the lowest density and the highest heat of combustion. With a critical temperature of  $-116^{\circ}$  F, it must be refrigerated before it can be handled in the liquid phase. Methane represents one extreme in this analysis in practically all properties. It is readily available as natural gas.

(2) Ethene was included in this analysis because of its superior combustion properties. Its flammability limits, in terms of fuel-air ratio, are wider and its flame speed is much greater than those for other fuels. For these reasons it might yield high combustion efficiencies and greater combustion stability at severe engine operating conditions.

(3) Propane is available as liquefied petroleum gas. It has a critical temperature of  $206^{\circ}$  F permitting it to be stored as a liquid without refrigeration; however, its vapor pressure is high, about 12 atmospheres at  $100^{\circ}$  F. The freezing point of propane ( $-306^{\circ}$  F) is the lowest for the hydrocarbons, and its thermal stability is quite high. In both heat of combustion and density propane is roughly halfway between methane and the conventional jet fuels.

(4) The isopentane-isohexane blend containing 42 weight percent isopentane is believed to be one of the lowest freezing binary blends of normally liquid hydrocarbons. As such it could be cooled to very low temperatures if added heat-sink capacity was needed with a normally liquid fuel.

(5) Aviation gasoline is the lowest freezing and most volatile of the conventional aircraft fuels. It would have a greater heat-sink capacity than current jet fuels, especially if it were precooled to a low initial temperature and allowed to vaporize when acting as a heat sink. The availability of aviation gasoline is somewhat limited and the cost moderately high because of octane number requirements. However, there would be no such requirement for turbojet use, and the fuel proposed herein is aviation gasoline only in terms of volatility and not in terms of knock rating. As such it should be readily available. It represents a fuel with properties that are quite familiar to the airframe and petroleum industries.



4220 (6) The JP-4 fuel used herein as the reference fuel is the average quality JP-4 fuel of reference 1. Recent experience with this type of fuel has shown that many batches have heat-sink capacities insufficient to meet some current needs. When heated to between 300° and 400° F in turbojet oil-to-fuel heat exchangers, many fuels form solid degradation products which impair engine performance. In this report it is assumed that the fuel is moderately stable and can be used up to 400° F without trouble. This JP-4 fuel then represents a good, but not outstanding, current jet fuel.

(7) The fuel designated as JP-z has a boiling range of 438° to 548° F and an API gravity of 34.5°. Aromatic content is very low (2 percent) and naphthene (cycloparaffin) content very high. The JP-z fuel has a very high thermal stability, as indicated by outstanding performance in a prototype stability tester. While the availability of this particular material is limited, it is probable that fuels of equal thermal stability will become widely available through continued research on this problem. The JP-z fuel then represents the thermally stable fuels which can reasonably be expected within the next few years.

The properties listed in table I were derived from the following sources: The freezing points, boiling points, and critical temperatures of the single-component fuels are from reference 2. The freezing point of the isopentane-isohexane blend was estimated from cryoscopic constants given in reference 3, and the freezing points for the JP-4 and JP-z fuels are experimental values. Aviation gasoline has a poorly defined freezing point; it slowly becomes more cloudy and more viscous as the temperature is lowered. It was assumed that this fuel could be used down to the temperature at which the viscosity is 15 centistokes. This temperature is about -160° F and is used as the lower limiting value. Raoult's law was used to calculate the boiling point of the isopentane-isohexane blends. The boiling points listed for the commercial fuels are the bubble points at 1 atmosphere from equilibrium flash vaporization curves. The critical temperatures of the multicomponent fuels are estimated by the method given in reference 2. Heats of combustion for the single-component fuels and for the isopentane-isohexane blend were taken directly or calculated from reference 3; for the others the aniline-gravity correlation (ref. 1) was used. The several combustion properties that are listed were taken or estimated from data given in the appendixes of reference 4.

Figure 1, showing enthalpy-temperature relations, was developed largely from the plots and correlations of reference 2 using data from reference 5 to fill in the lowest temperature portions of the methane, ethene, and propane curves. For figure 2, the vapor-pressure - temperature curves for methane, ethene, and propane were taken from reference 2, the isopentane-isohexane pressures calculated from Raoult's law, and the curves for the commercial fuels taken from reference 1 or estimated by methods given therein. The density-temperature relations of figure 3 were, for

the single component fuels and for the isopentane-isohexane blend, taken directly or estimated from reference 2; for the others, equation (4) of reference 1 was used. The dashed-line portions of the ethene and propane curves are linear extrapolations beyond the lowest temperature data available.

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TABLE I. - PROPERTIES OF SEVERAL HYDROCARBON FUELS

	Methane	Ethene	Propane	Isopentane- isohexane blend	Aviation gasoline	JP-4 fuel	JP-z fuel
Specific gravity, 60°/60°				0.644	0.693	0.773	0.854
Freezing point, °F	-296	-273	-306	-279		-85	-75
Boiling point, °F	-259	-155	-44	<sup>a</sup> 104	<sup>a</sup> 145	<sup>a</sup> 210	<sup>a</sup> 455
Critical temperature, °F	-116	50	206	400	500	640	825
Net heat of combustion, Btu/lb							
From liquid fuel				19,247	<sup>b</sup> 19,070	<sup>b</sup> 18,680	<sup>b</sup> 18,500
From gaseous fuel	21,500	20,275	19,930	19,395	19,240	18,840	18,645
Lean flammability limit							
Percent by volume	4.4	2.7	2.0	<sup>c</sup> 1.2	<sup>c</sup> 1.0	<sup>c</sup> 0.80	<sup>c</sup> 0.56
Fuel-air ratio	0.027	0.028	0.033	<sup>c</sup> 0.034	<sup>c</sup> 0.034	<sup>c</sup> 0.035	<sup>c</sup> 0.035
Rich flammability limit							
Percent by volume	15.5	>39	11.4	<sup>c</sup> 7.9	<sup>c</sup> 6.7	<sup>c</sup> 5.6	<sup>c</sup> 4.3
Fuel-air ratio	0.095	>0.41	0.18	<sup>c</sup> 0.24	<sup>c</sup> 0.25	<sup>c</sup> 0.26	<sup>c</sup> 0.28
Spontaneous ignition temperature, °F	1170	914	940		844	502	475
Maximum fundamental flame velocity, cm/sec	37	75	43	40	<sup>e</sup> 38	<sup>e</sup> 38	<sup>d</sup> 40

<sup>a</sup>Bubble point.<sup>b</sup>From correlation with aniline-gravity product.<sup>c</sup>From equations (27) to (30) (ref. 1).<sup>d</sup>Estimate.<sup>e</sup>Unpublished NACA data.

TABLE II. - HEAT-SINK CAPACITIES OF SEVERAL FUELS

Fuel	Initial temperature, °F	Final temperature, °F	Vapor pressure at final temperature, atm	Vaporization assumed	Heat-sink capacity	
					Btu/lb	Fraction of heat of combustion
Methane	-259	1245	(a)	Yes	1320	0.061
	-286	1245	(a)	Yes	1345	.062
	-259	<sup>c</sup> 1000	(a)	Yes	1085	.051
	-286	<sup>c</sup> 1000	(a)	Yes	1110	.052
Ethene	-155	985	(a)	Yes	785	.039
	-263	985	(a)	Yes	850	.042
Propane	-44	855	(a)	Yes	705	.035
	-296	855	(a)	Yes	830	.042
Isopentane- isohexane	100	825	(a)	Yes	595	.031
	-269	825	(a)	Yes	770	.040
Aviation gasoline	100	780	(a)	Yes	560	.029
	-160	780	(a)	Yes	685	.036
JP-4	100	<sup>b</sup> 400	7.6	No	165	.009
	-75	<sup>b</sup> 400	7.6	No	240	.013
JP-z	100	825	(a)	Yes	545	.029
	-65	825	(a)	Yes	610	.032
	100	800	20	No	435	.024

<sup>a</sup>Above critical temperature.<sup>b</sup>Assumed gum limited at 400° F.<sup>c</sup>Assumed that final temperature limited by exchanger drive temperature at 1000° F.

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TABLE III. - HEAT-SINK REQUIREMENTS FOR THREE TURBOJET ENGINES

[Values in parentheses are assumed; see text.]

	Required heat-sink capacity, fraction of heat of combustion								
	Engine A (2000° R turbine-inlet temperature and afterburner)			Engine B (2500° R turbine-inlet temperature and afterburner)			Engine C (3000° R turbine-inlet temperature, no afterburner)		
Altitude, ft	60,000	60,000		40,000	60,000	65,000	40,000	60,000	65,000
Mach number	1.0	1.9		1.0	1.9	2.5	1.0	1.9	2.5
Heat source									
Fuel pump	0.002	0.0005		(0.001)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)
Fuel-oil exchanger <sup>a</sup>	.005	.002		(.005)	(.002)	(.002)	(.005)	(.002)	(.002)
Turbine cooling				.006	.006	.006	.024	.027	.028
Total	0.007	0.0025		0.012	0.008	0.008	0.030	0.029	0.030

<sup>a</sup>Includes loads for alternator drive, accessory gear box and high-capacity lubrication pump for operating engine hydraulic systems.

TABLE IV. - HEAT-SINK CAPACITIES REMAINING FOR NON-ENGINE USE

(a) Engine A (2000° R turbine-inlet temperature and afterburner).

Fuel	Initial temperature, °F	Final temperature, °F	Available heat sink, fraction of heat of combustion	At 60,000 ft, and Mach 1.0			At 60,000 ft, and Mach 1.9		
				Engine requirement, fraction of heat of combustion	Sink left available for other uses		Engine requirement, fraction of heat of combustion	Sink left available for other uses	
					Fraction of heat of combustion	Btu/lb fuel		Fraction of heat of combustion	Btu/lb fuel
Methane	-259	1000	0.051	0.007 ↓	0.044	950	<sup>a</sup> 0.003 ↓	0.048	1030
	-286	1000	.052		.045	970		.049	1050
Ethene	-155	985	.039		.032	650		.036	730
	-263	985	.042		.035	710		.039	790
Propane	-44	855	.035		.028	560		.032	640
	-296	855	.042		.035	700		.039	780
Isopentane-isohexane	100	825	.031		.024	470		.028	540
	-269	825	.040		.033	640		.037	720
Aviation gasoline	100	780	.029		.022	420		.026	500
	-160	780	.036		.029	560		.033	630
JP-4	100	<sup>b</sup> 400	.009		.002	35		.006	110
	-75	<sup>b</sup> 400	.013		.006	110		.010	190
JP-z	100	825	.029		.022	410		.026	480
	-65	825	.032		.025	470		.029	540
	100	<sup>b</sup> 800	.025		.018	330		.022	410

<sup>a</sup>Rounded from 0.0025 in table III.<sup>b</sup>Final state of fuel, liquid phase.

TABLE IV. - Continued. HEAT-SINK CAPACITIES REMAINING FOR NON-ENGINE USE

(b) Engine B (2500° R turbine-inlet temperature and afterburner).

Fuel	Initial temperature, °F	Final temperature, °F	Available heat sink, fraction of heat of combustion	At 40,000 ft, and Mach 1.0			At 60,000 ft, and Mach 1.9			At 65,000 ft, and Mach 2.5		
				Engine requirement, fraction of heat of combustion	Sink left available for other uses		Engine requirement, fraction of heat of combustion	Sink left available for other uses		Engine requirement, fraction of heat of combustion	Sink left available for other uses	
					Fraction of heat of combustion	Btu/lb fuel		Fraction of heat of combustion	Btu/lb fuel		Fraction of heat of combustion	Btu/lb fuel
Methane	-259	1000	0.051	↓	0.039	840	↓	0.043	920	↓	0.043	920
	-286	1000	.052		.040	860		.044	950		.044	950
Ethene	-155	985	.039		.027	550		.031	630		.031	630
	-263	985	.042		.030	610		.034	690		.034	690
Propane	-44	855	.035		.023	460		.027	530		.027	530
	-296	855	.042		.030	600		.034	680		.034	680
Isopentane- isohexane	100	825	.031		.019	370		.023	450		.023	450
	-269	825	.040		.028	540		.032	620		.032	620
Aviation gasoline	100	780	.029		.017	330		.021	400		.021	400
	-160	780	.036		.024	460		.028	540		.028	540
JP-4	100	<sup>a</sup> 400	.009		.003	(b)		.001	20		.001	20
	-75	<sup>a</sup> 400	.013		.001	20		.005	90		.005	90
JP-z	100	825	.029		.017	320		.021	390		.021	390
	-65	825	.032		.020	370		.024	450		.024	450
	100	<sup>a</sup> 800	.025		.013	240		.017	310		.017	310

<sup>a</sup>Final state of fuel, liquid phase.<sup>b</sup>Heat-sink capacity insufficient to meet engine requirements alone.



TABLE IV. - Concluded. HEAT-SINK CAPACITIES REMAINING FOR NON-ENGINE USE

(c) Engine C (3000° R turbine-inlet temperature, no afterburner).

Fuel	Initial temperature, °F	Final temperature, °F	Available heat sink, fraction of heat of combustion	At 40,000 ft, and Mach 1.0			At 60,000 ft, and Mach 1.9			At 65,000 ft, and Mach 2.5		
				Engine requirement, fraction of heat of combustion	Sink left available for other uses		Engine requirement, fraction of heat of combustion	Sink left available for other uses		Engine requirement, fraction of heat of combustion	Sink left available for other uses	
					Fraction of heat of combustion	Btu/lb fuel		Fraction of heat of combustion	Btu/lb fuel		Fraction of heat of combustion	Btu/lb fuel
Methane	-259	1000	0.051	0.030	0.021	450	0.029	0.022	470	0.030	0.021	450
	-286	1000	.052		.022	470		.023	490		.022	470
Ethene	-155	985	.039		.009	180		.010	200		.009	180
	-263	985	.042		.012	240		.013	260		.012	240
Propane	-44	855	.035		.005	100		.006	120		.005	100
	-296	855	.042		.012	240		.013	260		.012	240
Isopentane- isohexane	100	825	.031		.001	20		.002	40		.001	20
	-269	825	.040		.010	190		.011	220		.010	190
Aviation gasoline	100	780	.029		-.001	(a)		0	0		-.001	(a)
	-160	780	.036		.006	120		.007	130		.006	120
JP-4	100	<sup>b</sup> 400	.009		-.021	(a)		-.020	(a)		-.021	(a)
	-75	<sup>b</sup> 400	.013		-.017	(a)		-.016	(a)		-.017	(a)
JP-z	100	825	.029		-.001	(a)		0	0		-.001	(a)
	-65	825	.032		.002	35		.003	55		.002	35
	100	<sup>b</sup> 800	.025		-.005	(a)		-.004	(a)		-.005	(a)

<sup>a</sup>Heat-sink capacity insufficient to meet engine requirements alone.<sup>b</sup>Final state of fuel, liquid phase.

TABLE V. - EFFECT OF FUEL VARIABLES ON AIRCRAFT RANGE

Fuel	Initial temperature,	Aircraft range relative to that obtained with JP-4 fuel at 100° F			
		With engine B		With engine C	
		Inter-ceptor	Bomber	Inter-ceptor	Bomber
JP-4	100	<sup>a</sup> 1.00	<sup>a</sup> 1.00	<sup>a</sup> 1.00	<sup>a</sup> 1.00
	-75	<sup>a</sup> 1.02	<sup>a</sup> 1.01	<sup>a</sup> 1.02	<sup>a</sup> 1.01
Methane	-259	1.15	1.16	1.11	1.15
	-286	1.16	1.16	1.12	1.16
Ethene	-155	1.10	1.10	1.07	1.11
	-263	1.13	1.12	1.10	1.11
Propane	-44	1.07	1.07	1.05	1.07
	-296	1.12	1.10	1.09	1.09
Isopentane-isohexane	100	1.03	1.04	1.02	1.04
	-269	1.09	1.07	1.07	1.06
Aviation gasoline	100	1.03	1.04	1.03	1.03
	-160	1.07	1.05	1.06	1.05
JP-z	100	1.02	1.01	1.02	1.01
	-65	1.03	1.02	1.03	1.01
	100	<sup>a</sup> 1.00	<sup>a</sup> 0.99	<sup>a</sup> 1.00	<sup>a</sup> 0.99

<sup>a</sup>Fuel reaches engine in liquid phase. All other data with fuel reaching engine in vapor phase.

TABLE VI. - RUNWAY HOLDING TIME

BEFORE FUEL VAPOR PRESSURE EXCEEDS

2.0 ATMOSPHERES ABSOLUTE

[Ambient temperature, 80° F]

Fuel	Initial fuel temperature, °F	Holding time, hrs	
		Inter-ceptor	Bomber
Methane	-259	3.8	6.6
	-286	10.6	17.9
Ethene	-155	6.6	11.7
	-263	37.5	64.4
Propane	-44	16.6	30.2
	-296	94.0	167

TABLE VII. - ESTIMATED AVAILABILITIES AND COSTS FOR SEVERAL FUELS

Fuel	Unit	Availability per year						Current or recent cost, dollars	
		Actual			Potential			Per unit	Per 10 <sup>6</sup> Btu
		Year	Units	Btu	Year	Units	Btu		
Methane (natural gas)	cu ft	1954	1.1×10 <sup>13</sup>	1.1×10 <sup>16</sup>	1960	1.5×10 <sup>13</sup>	1.5×10 <sup>16</sup>	0.0004	0.45
Methane as liquid	gal							.055	.88
Ethene	lb	1954	2×10 <sup>9</sup>	4×10 <sup>13</sup>	1962	4×10 <sup>9</sup>	8×10 <sup>13</sup>	.0475	2.40
Propane	gal	1954	5.0×10 <sup>9</sup>	4.2×10 <sup>14</sup>	1960	7.3×10 <sup>9</sup>	6×10 <sup>14</sup>	.055	0.65
Isopentane-isohexane	gal	1945	2.6×10 <sup>8</sup>	2.7×10 <sup>13</sup>	1960	5×10 <sup>8</sup>	5×10 <sup>13</sup>	.20	1.90
Aviation gasoline <sup>a</sup>	gal	1956	3.3×10 <sup>9</sup>	3.7×10 <sup>14</sup>	1960	3×10 <sup>10</sup>	3×10 <sup>15</sup>	.15	1.40
JP-4	gal	1956	2.7×10 <sup>9</sup>	3.2×10 <sup>14</sup>	1960	3×10 <sup>10</sup>	3×10 <sup>15</sup>	.15	1.25
JP-z	gal	----	-----	-----	1960	8×10 <sup>9</sup>	1×10 <sup>15</sup>	1.00	7.50

<sup>a</sup>Current production based on true aviation gasoline; potential production (1960) and cost based on fuel with aviation gasoline volatility but with no octane number requirement.

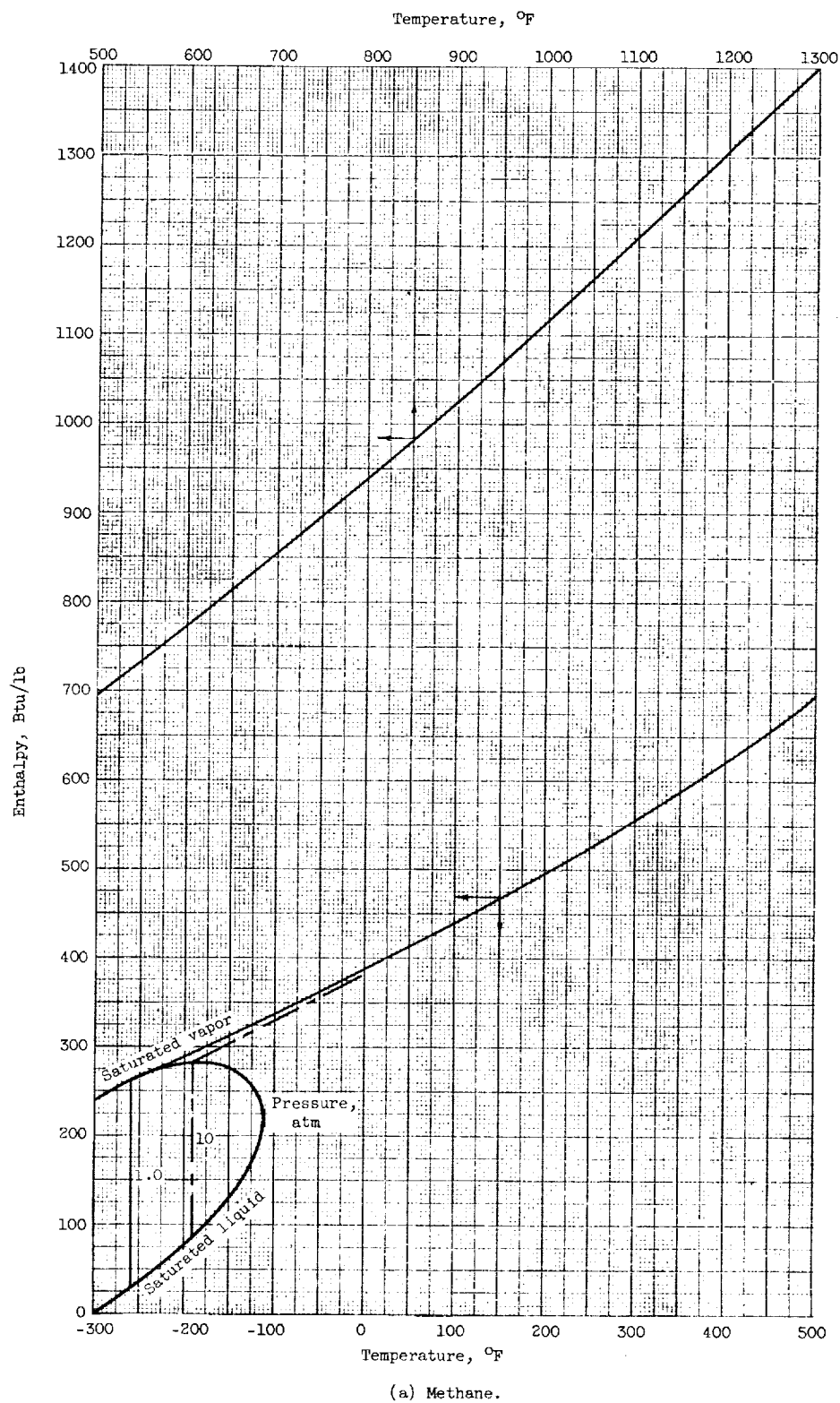
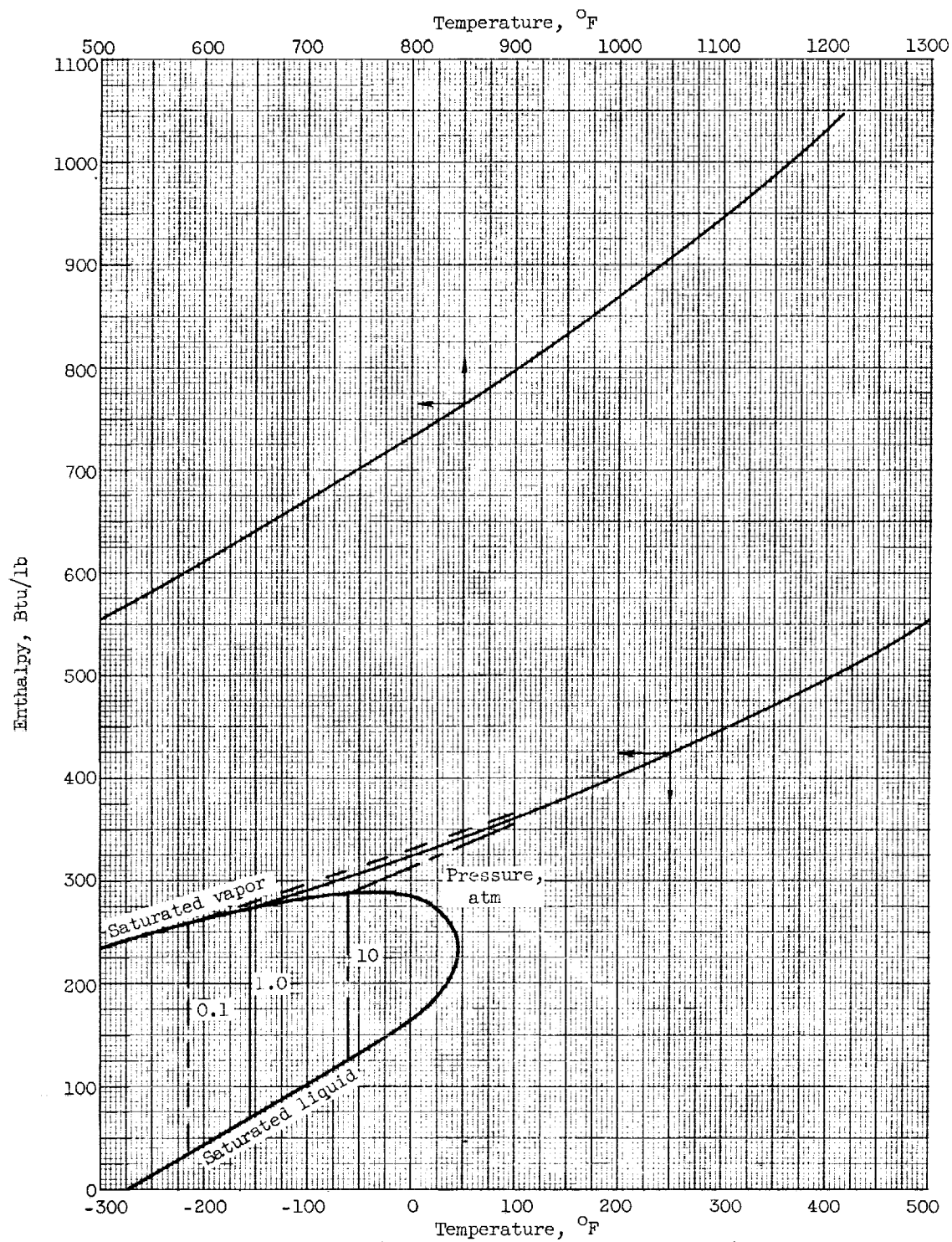
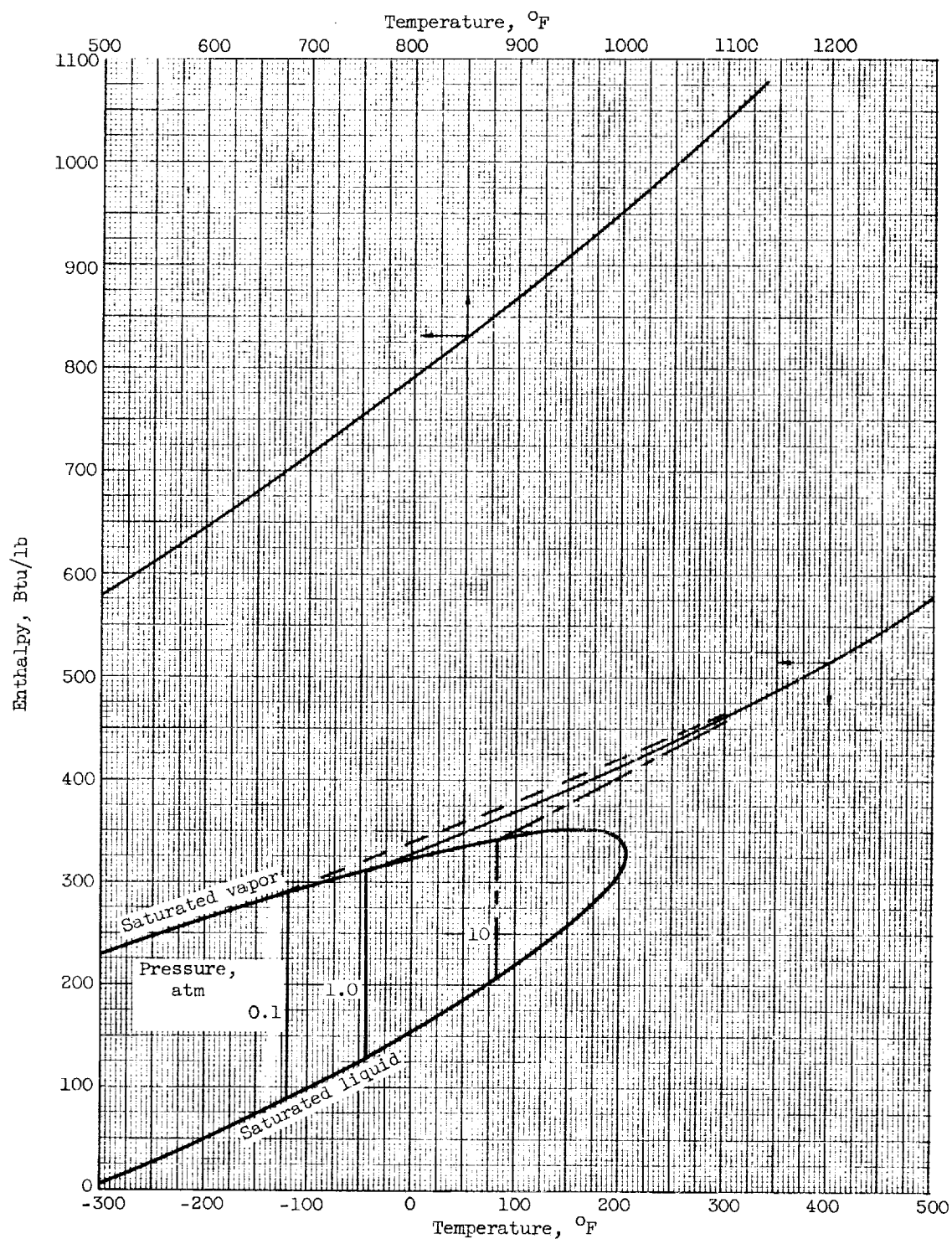


Figure 1. - Enthalpy as function of temperature (enthalpy base at freezing point).



(b) Ethene.

Figure 1. - Continued. Enthalpy as function of temperature (enthalpy base at freezing point).

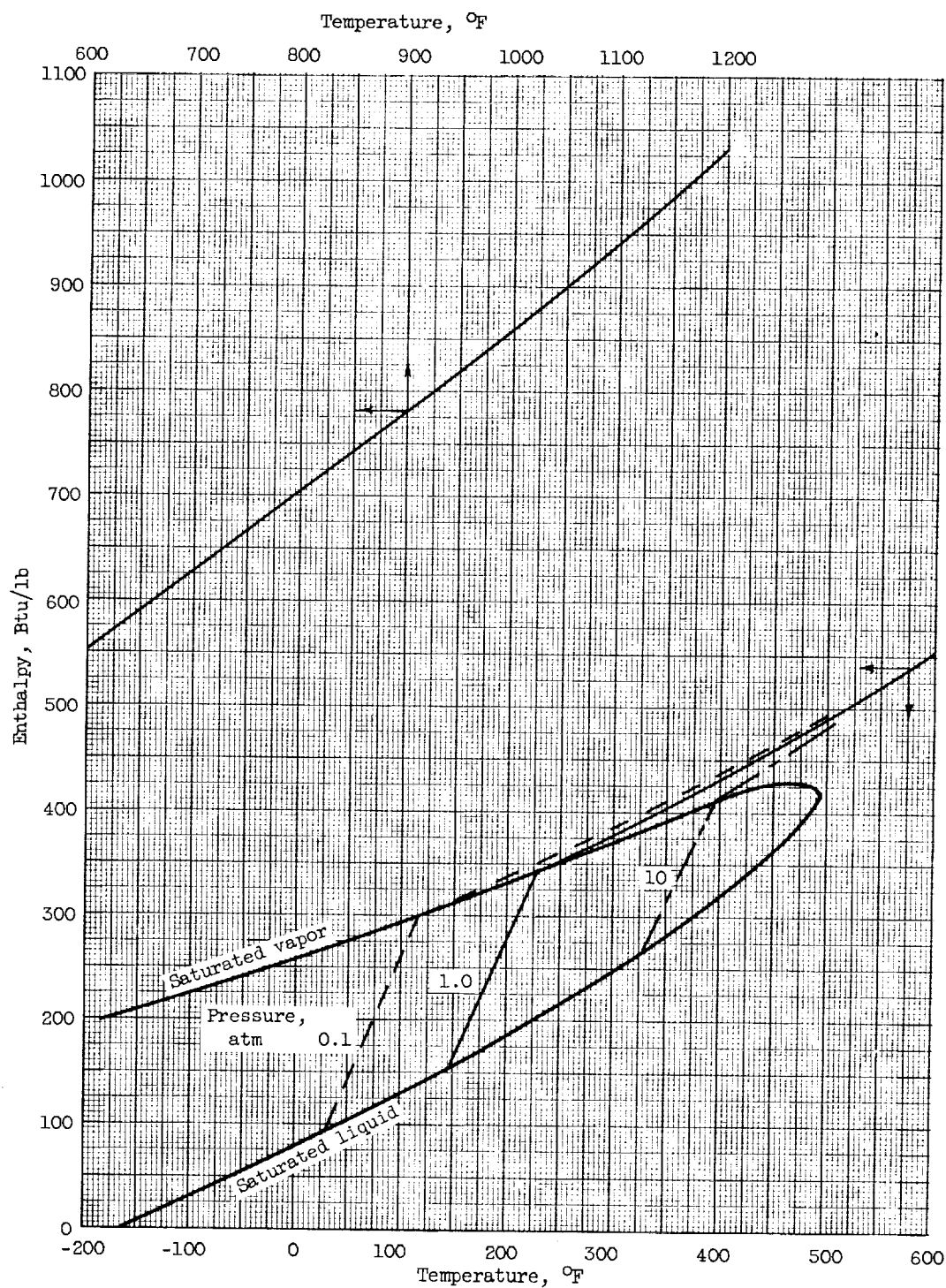


(c) Propane.

Figure 1. - Continued. Enthalpy as function of temperature (enthalpy base at freezing point).

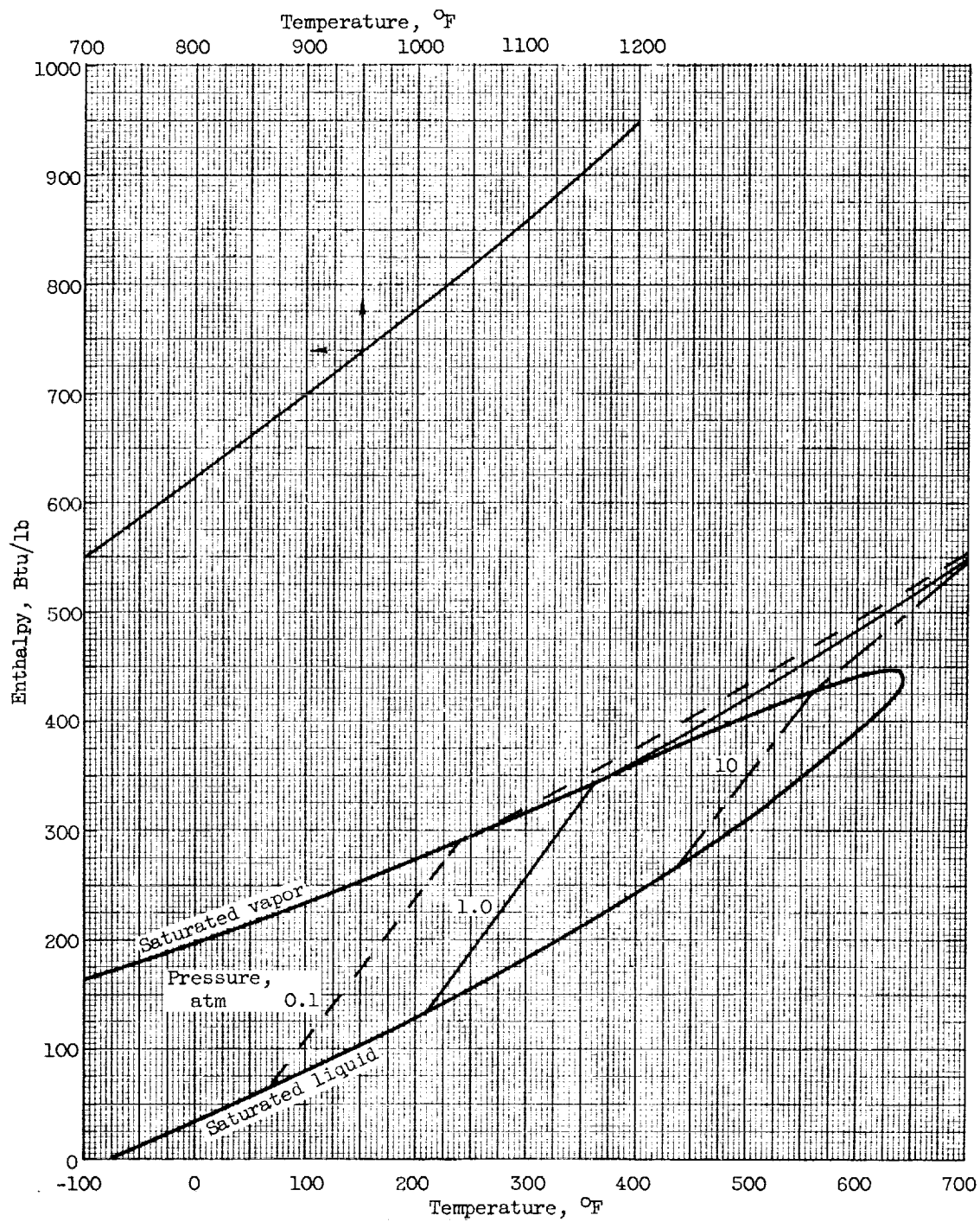


Figure 1. - Continued. Enthalpy as function of temperature (enthalpy base at freezing point).



(e) Aviation gasoline.

Figure 1. - Continued. Enthalpy as function of temperature (enthalpy base at freezing point).



(f) JP-4 fuel.

Figure 1. - Continued. Enthalpy as function of temperature (enthalpy base at freezing point).



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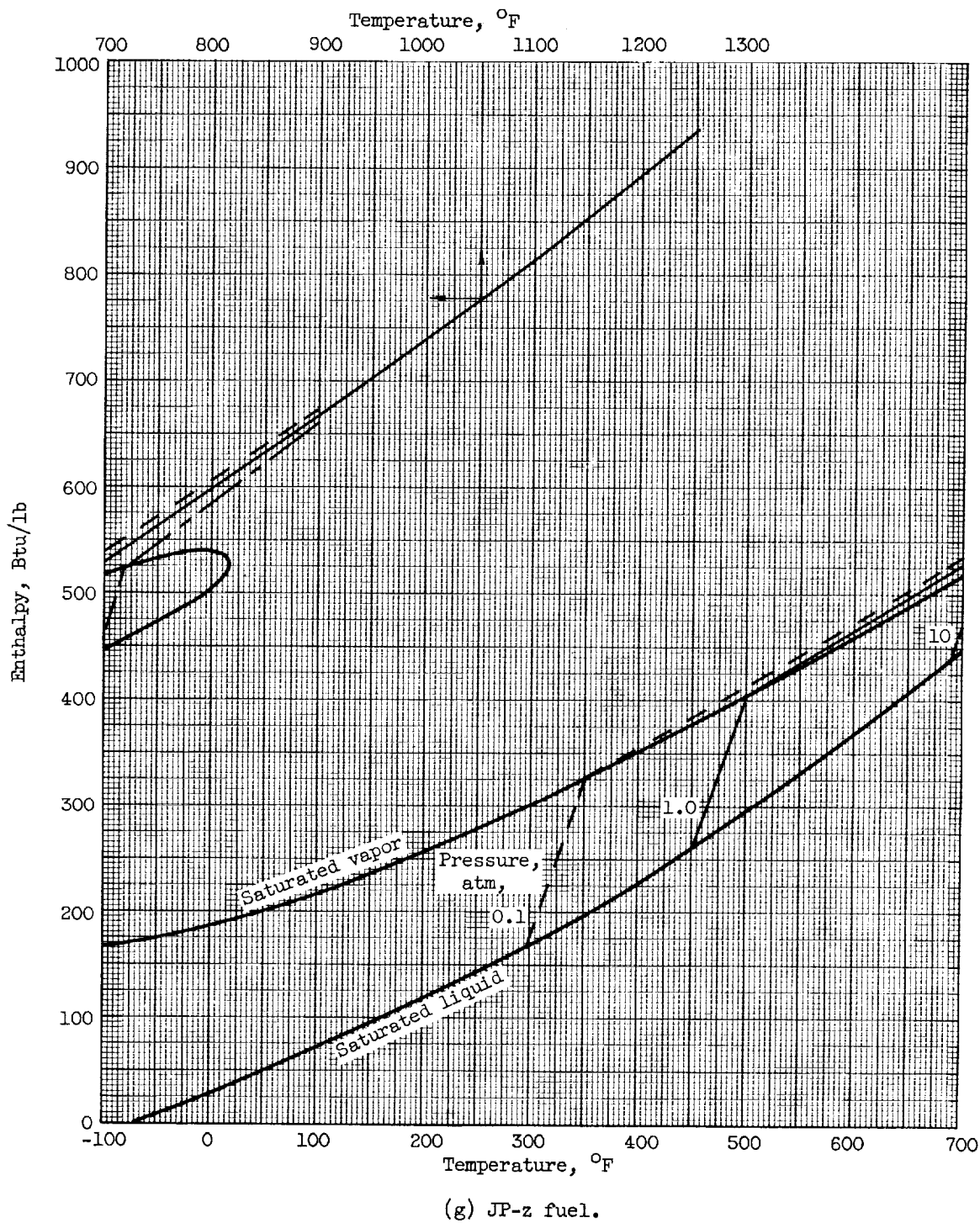


Figure 1. - Concluded. Enthalpy as function of temperature (enthalpy base at freezing point).

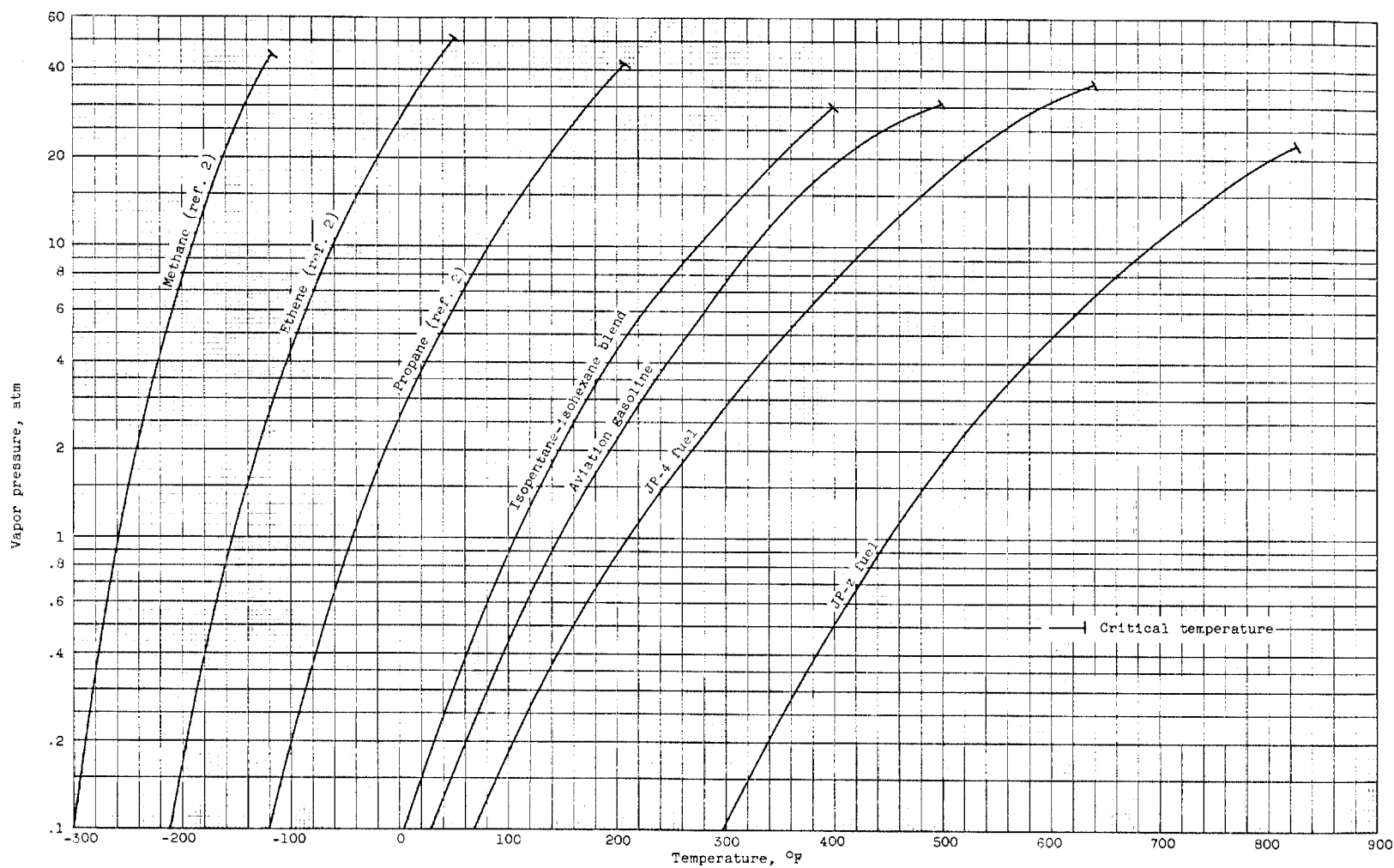


Figure 2. - Vapor-pressure - temperature curves for several fuels.

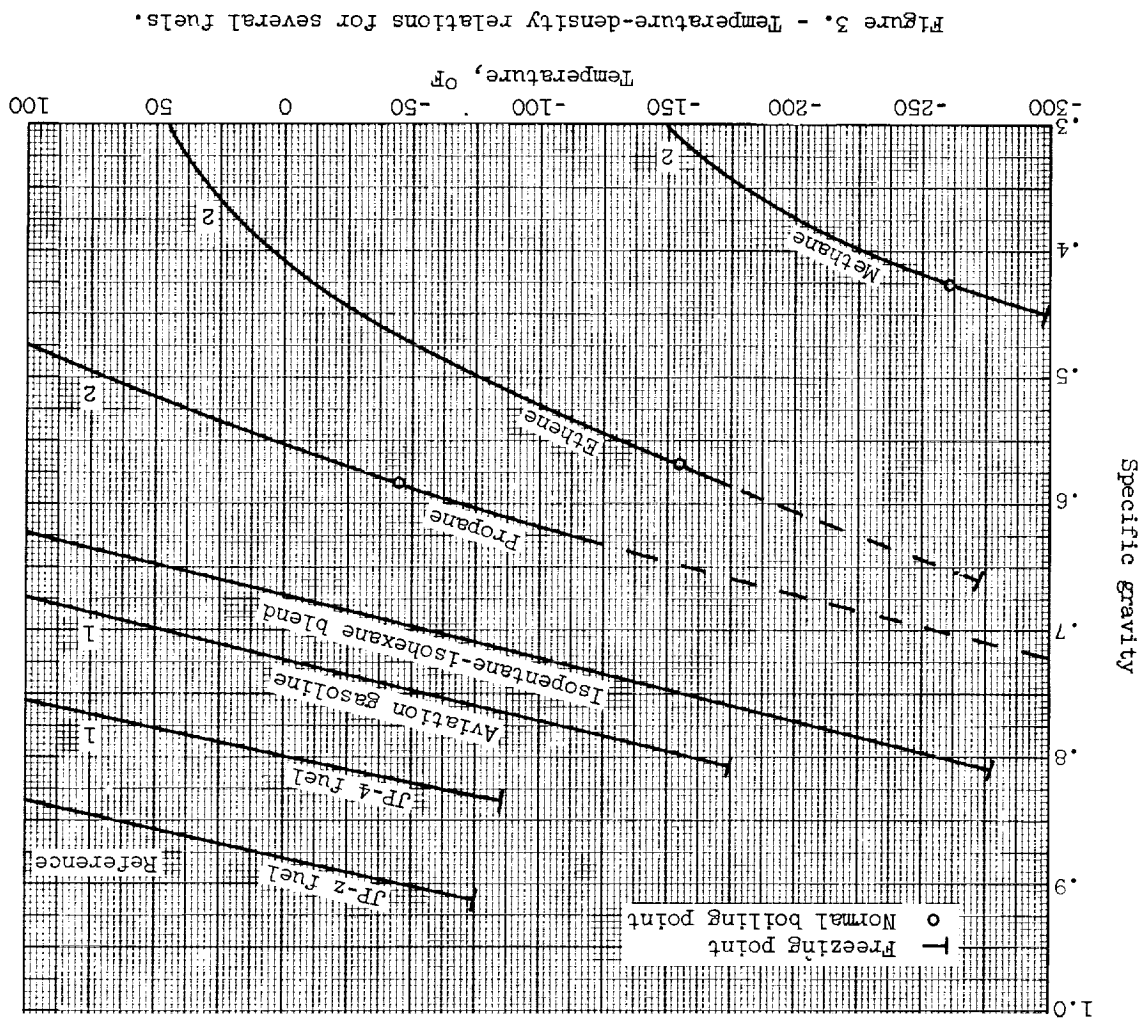


Figure 3. - Temperature-density relations for several fuels.

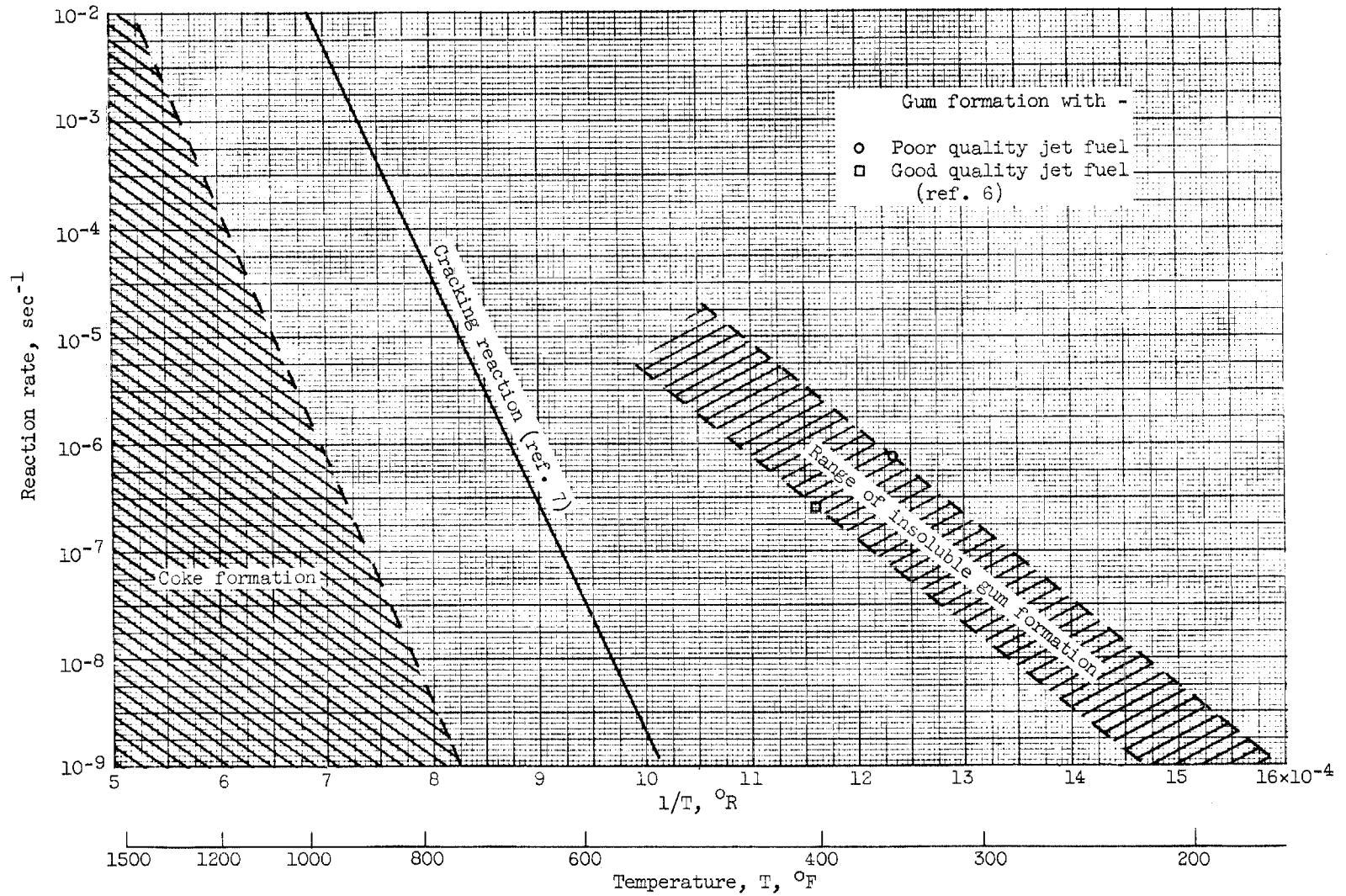


Figure 4. - Degradation reactions of JP-4 fuel.

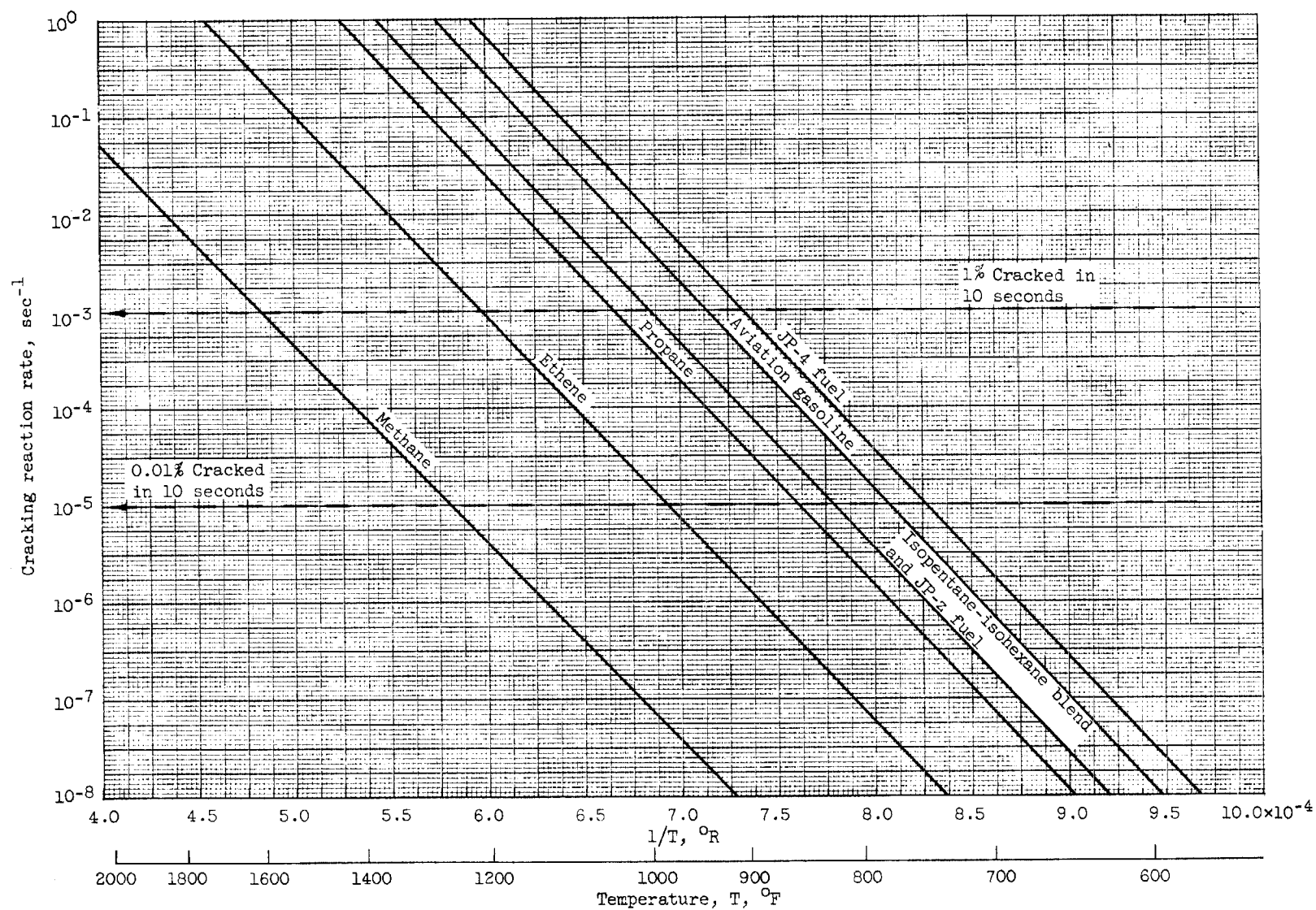


Figure 5. - Thermal cracking rates for several fuels.

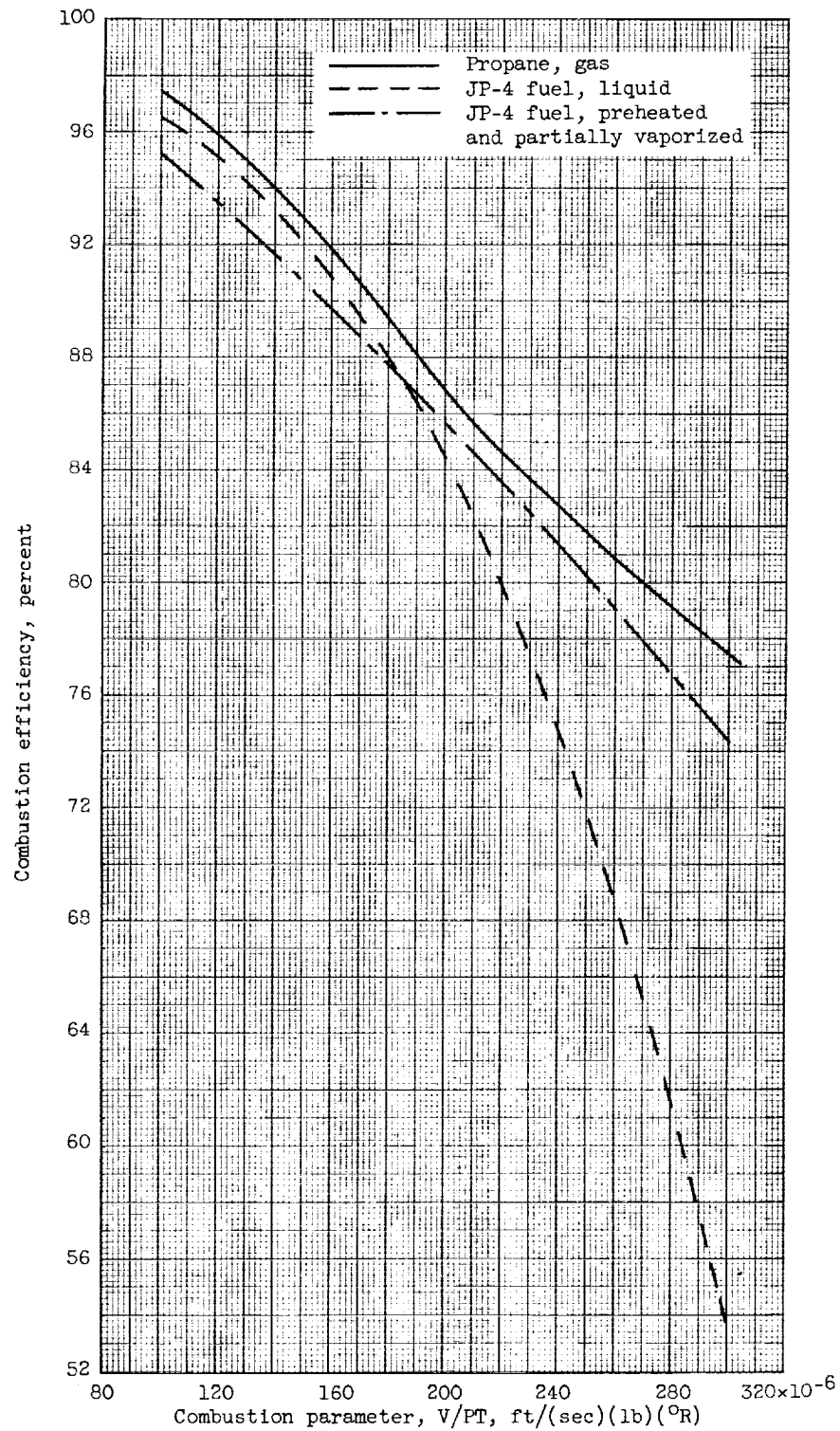


Figure 6. - Combustion efficiency as function of combustor parameter (ref. 14).